

# *PSVR* - Self-stabilizing Publish/Subscribe Communication for Ad-hoc Networks

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**Abstract.** This paper presents the novel routing algorithm *PSVR* for pub/sub systems in ad-hoc networks. Its focus is on scenarios where communications links are unstable and nodes frequently change subscriptions. *PSVR* presents a compromise of size and maintenance effort for routing tables due to sub- and unsubscriptions and the length of routing paths. Designed in a self-stabilizing manner it scales well with network size. The evaluation reveals that *PSVR* only needs slightly more messages than a close to optimal routing structure for publication delivery, and creates shorter routing paths than an existing self-stabilizing algorithm. A real world deployment shows the usability of the approach.

## 1 Introduction

Industrial wireless sensor networks are an emerging field for process monitoring and control that require dynamic forms of the many-to-many communication paradigm for data dissemination. This communication style is best supported by publish/subscribe (pub/sub) systems instead of request-reply messaging. In channel-based pub/sub systems, publishers assign each message to one of several channels which are known by all nodes. Subscribers express interest in one or more channels (a.k.a. subscribing to the channel) and only receive messages assigned to these. The pub/sub paradigm guarantees disseminating all messages to nodes with a subscription for that channel. The advantage is the loose coupling, i.e., publishers are unaware of the subscribers that receive their messages. Nodes can at any time give up subscriptions and create new ones.

The efficiency of message dissemination in pub/sub systems depends on the used routing strategy. The goal is to deliver each publication with a minimum number of messages to all subscribers. The minimum number of messages is used when the publication is routed along the Steiner tree for the publishing node and all nodes subscribing to the message's channel. Since Steiner trees are computationally too expensive many systems use a fixed spanning tree for routing. A publisher recursively forwards a message into those subtrees that contain a subscriber for the message's channel. This requires each node to provide the necessary information and does in general not result in the shortest routing path. Other systems organize their nodes into a virtual ring. A published message is then simply forwarded once around this ring and thereby delivered to all

subscribers. This does not require any routing tables and there is no need to distribute un-/subscriptions into the network. Unfortunately this requires at least as many messages as nodes in the virtual ring.

In this paper we consider scenarios where nodes frequently change their subscriptions, hence, an efficient update of the routing structure is required. Also delivery of publications must be guaranteed while subscriptions are changing. To meet this goal we propose the routing algorithm  $\mathcal{PSVR}$ , which is a significant extension of the algorithm in [14].  $\mathcal{PSVR}$  presents a compromise between the length of routing paths and the effort to maintain the routing tables. One of the core ideas is to augment routing on the virtual ring by shortcuts. We show that for a specific class of graphs on average the increase of the length of routing paths is bearable and updating a node's subscription list is simple. To increase system robustness and to tolerate the failure and recovery of links and nodes the proposed algorithms are self-stabilizing. The effectiveness of the proposed algorithm is shown through simulations using a realistic channel model and by a comparison with a self-stabilizing tree-based approach.

## 2 Related Work

The general state of the art for pub/sub systems for WSN is summarized in a recent survey [12]. Detti et al. classify pub/sub systems into pull and push systems [4]. In the first model nodes interested in a channel periodically flood the network with interest messages upon which nodes respond with cached publications for this channel via reverse paths. The number of sent messages is dominated by the frequency of issued interest messages – which reflects latency – and not by the number of subscriptions. Such an approach is of advantage in mobile environments where routing structures are quickly outdated. In the push model the number of messages sent mainly depends on the rate of publications and the number of subscribers, given a routing structure. For static environments this approach is of advantage. Baldoni et al. distinguish between message and subscription forwarding [1]. In the former case all publications are forwarded via a fixed spanning tree. Thus, the number of forwarded messages does not scale with the number of network nodes. Subscription forwarding permits to establish a routing structure that allows to forward publications to subscribers only. This way the number of forwarded messages is independent of the total number of nodes but depends on the number of subscribers and their positions.

Message forwarding is mainly of interest if the number of subscribers is large compared to the number of nodes and if the number of publications is low. Mires [15] is a pub/sub middleware for WSNs where the sink is the sole subscriber. Nodes advertise the data they can provide and the sink thereafter informs nodes about its interest. Routing is performed along a fixed tree. Fault tolerance is not considered. Proposed standards such as MQTT-S [7] and DDS [11] mainly address QoS and are not tailored towards resource constrained networks. Pub/sub systems such as Scribe use overlay networks based on distributed hash tables [2]. Overlay networks are logical networks on top of real network where

links correspond to paths in the underlying network, which are usually IP-based networks. Thus, this approach is unsuitable for WSNs. One of the first pub/sub system dedicated to wireless ad-hoc networks is described in [6]. A greedy algorithm builds a tree for each node which is used to route publications to subscribers. Fault tolerance is not addressed.

The first proposal for subscription forwarding is directed diffusion [8]. Each subscription sets up gradients in the network, these are used to deliver publications. Even so nodes cache information from previous subscriptions the message overhead is high. Negative reinforcement is used to eliminate loops. Directed diffusion provides some degree of fault tolerance by maintaining alternative paths.

We are only aware of two self-stabilizing pub/sub systems [9, 13]. Jaeger's system uses a broker overlay network to route publications to subscribers connected to brokers, these only forward the data [9]. Subscriptions and advertisements are used to generate routing tables. The leasing technique is used to fix possible faults in these routing tables. The renewal of leases is triggered by periodically dispensed subscription messages, an expired lease leads to the removal of the entry. Shen uses a spanning tree to route publications [13]. Nodes maintain routing tables to forward publications. To provide fault tolerance routing tables are exchanged periodically. This mechanism cannot tolerate all types of faults, e.g., the concurrent loss of routing entries in several nodes. A self-repairing content-based routing algorithm is described in [10].

A disadvantage of all tree-based routing approaches is that only the  $n - 1$  communication links of the tree are used [3]. For dense networks this excludes the majority of links and leads to long routing paths. To circumvent this disadvantage a self-stabilizing pub/sub system based on a virtual ring is introduced in [14]. A virtual ring is a directed closed path over all nodes. It allows for a very simple dissemination of publications without requiring knowledge of the topology, but forwarding paths can be much longer than the shortest paths. The remedy used in [14] is to use edges that are not part of the ring as short-cuts. The result is a compromise between the complexity of the routing tables and the lengths of the forwarding paths. A positive aspect is that it is easy to adapt the structure to new subscribers, but the approach of [14] has several shortcomings. Firstly, nodes may receive a subscription several times. Secondly, subscription messages are forwarded to all subscribers. Also publications are not discarded by the last subscriber on the ring but sent further along the ring. Unsubscriptions are only marginally addressed in [14]. If a stale routing table entry is not refreshed within the leasing period, it is removed and all further messages are routed along the virtual ring instead. This leads to a temporary loss of routing information, hence, to longer routing paths.

### 3 Foundation

Let  $G = (V, E)$  be an undirected graph with  $n$  nodes. A virtual ring is a closed path over all nodes formally defined as follows.

**Definition 1.** A sequence  $R = \langle v_0, \dots, v_{l-1} \rangle$  of nodes  $v_i \in V$  is called a *virtual ring* if each  $v \in V$  appears at least once in  $R$  and if each  $v_i$  is a neighbor of  $v_{i+1}$  (indices are taken modulo  $l$ );  $l$  is called the *length* of  $R$ . For  $v \in V$  each  $i$  with  $v = v_i$  is called a *position* of  $v$ . The list of positions of  $v$  is denoted by  $Pos(v)$ .

Each connected graph possesses a virtual ring. Note that  $l = \sum_{v \in V} |Pos(v)|$ . For a virtual ring of short length the sets  $Pos(v)$  must be small. Only Hamiltonian graphs have virtual rings with  $|Pos(v)| = 1$  for each  $v \in V$  (i.e.,  $l = n$ ). A depth-first traversal of a tree  $T$ , where every node visit is recorded with an incremented value, determines a virtual ring  $R$  and all node positions. A node  $v$  has as many positions on  $R$  as  $v$  has neighbors in  $T$ , i.e.,  $l = 2(n - 1)$ . Figure 1 shows a spanning tree (bold edges) for a topology with six nodes (left).

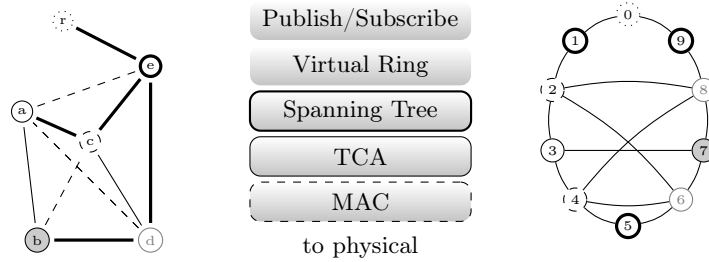


Fig. 1: Topology; layered system architecture; corresponding virtual ring graph.

As in [14] we use a topology control algorithm (TCA) to mark a communication graph using only high quality, bi-directional, stable links. The chosen TCA is dynamic, deteriorating links are removed, while new promising links are added. The number of maintained neighbors is limited to  $C_N$  to accommodate restricted memory resources. The TCA acts as a message filter for broadcasted messages. Messages received from nodes that are not in the current neighbor set are not dispatched to upper layers. Thus, links not chosen by the TCA are transparent to upper layers. In Fig.1 (left) edges selected by the TCA are depicted as solid lines ( $C_N = 3$ ) while dashed edges were excluded. To benefit from links selected by the TCA that are not part of the virtual ring, *shortcuts* are introduced.

**Definition 2.** An edge  $(v_i, v_j)$  with  $j \neq i + 1$  is called a *shortcut* in a ring  $R$ .

In the following a virtual ring based on depth-first traversal is interpreted as a graph  $G_R$  where the nodes correspond to the positions of the original nodes. If  $G$  has  $n$  nodes, the virtual ring  $G_R$  graph has  $2(n - 1)$  nodes. The edges of  $G_R$  correspond to the edges of  $R$  and the shortcuts of  $R$  in  $G$ . Figure 1 (right) shows the virtual ring graph emerging from the given topology, the selection conducted by the TCA, and the spanning tree on the left, i.e.,  $R = \langle r, e, c, a, c, e, d, b, d, e \rangle$ . The edge between  $c$  and  $d$  in the topology, results in the shortcuts between

positions 2, 4 and 6, 8 in  $G_R$ . A node's representation in the topology corresponds to the appearance of its position on  $G_R$ .

With the virtual ring and the shortcuts in place, the pub/sub routing algorithm can be explained. Nodes can take the role of publishers, subscribers, both or none. Independent of their role, nodes forward messages via links of the virtual ring graph. Two message types are used: *subscriptions* to build and update routing tables and *publications* to carry the data. Routing on each channel is independent. The creation of channels is not explicitly stated in [14]. In the following we assume that channels are defined prior to system start-up, and their existence is known to all nodes. Hereafter, since channels are independent of each other, if not stated otherwise only a single channel is considered.

A trivial way to route publications on the virtual ring is to consecutively hand them to each successor and to deliver them if a corresponding subscription exists. When a publication returns to its originator it is discarded. With the virtual ring in place, routing tables are trivial. Even though this procedure is simple and memory-conserving, nodes with multiple positions receive publications repeatedly. Each message is forwarded  $l$  times, i.e., independent of the number of subscribers. This decreases robustness due to the increased message loss probability and increases latency. Furthermore, each node receives all publications in the network regardless of being a subscriber or not. This trivial routing scheme is significantly improved in [14] by using shortcuts. These lead on average to shorter routing paths. Using the leasing technique, it is shown that the system is self-stabilizing and therefore inherent fault-tolerant. Nevertheless the approach is flawed, shortcomings in every section of the pub/sub system have been identified and solutions to those issues are presented next.

## 4 Publish/Subscribe on Virtual Rings

The architecture of  $\mathcal{PSVR}$  is shown in Fig. 1. For details about the virtual ring, the spanning tree, and the TCA we refer to [14]. The spanning tree layer is slightly augmented to enhance the dissemination of subscriptions.

**Routing tables in  $\mathcal{PSVR}$ .** Each node  $v$  maintains a routing structure  $RS(v)$  in form of a  $n_c \times n_p$  matrix,  $n_c$  denotes the number of channels and  $n_p = |Pos(v)|$ .  $RS$  stores tuples in the form  $\langle ns, t_s, nstmp \rangle$ . When a message for the  $c_i^{th}$  channel is received at the  $p_j^{th}$  position, then  $RS(v)[c_i, p_j].ns$  is the position of the subscriber for channel  $c_i$  which is counter clock wise (ccw) closest to the  $p_j^{th}$  position (called forwarding position). The components  $t_s, nstmp$  are used for unsubscriptions (see Sec. 4.3). Before described the routing of publications the novel subscription dissemination on the pub/sub and on the tree layer is presented.

### 4.1 Subscriptions

Subscription messages are used to maintain the routing structures  $RS$  at all nodes. Lost subscription messages do not lead to a permanent omission of pub-

lications, because the leasing technique guarantees the renewal of a subscription within time  $\delta_S$ .

**Subscription Distribution Range.** In  $RS(v)$  the next ccw subscriber for each position of  $v$  is stored. A newly subscribing node  $w$  requires that nodes update their routing structure. In particular a node  $u$  needs to update  $RS(u)$  if and only if there exists a position  $p_w \in Pos(w)$  and a position  $p_u \in Pos(u)$  such that  $p_w$  is ccw in between  $p_u$  and  $p_u^f$ , where  $p_u^f$  is the according forwarding position in  $RS(u)$  for  $p_u$ . That is, only the positions between a new subscriber  $w$  and the *clock wise* closest subscriber  $u$ , i.e., all nodes in the interval  $[u, w)$ , need to receive subscriptions from  $w$ . Figure 2 shows the stored next subscriber. Positions in the interval  $[7, 9)$  record position 9 as next subscriber. All other positions, i.e., the positions in the interval  $[9, 7)$ , store position 7.

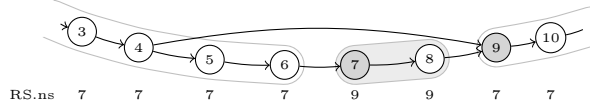


Fig. 2: Virtual ring with two subscribers (gray).

**Distributed Subscription Routing over the Tree.** Subscription messages can be spread faster and with viewer messages if distributed over disjoint paths. Thus, we spread subscription messages (not publications) over the spanning tree built to construct the virtual ring. In the spanning tree layer subscription messages are distributed through broadcasts. For maintenance of  $RS$  messages of the form  $SUB\langle r, C_S, P \rangle$  are distributed with period  $\delta_S$ . The spanning tree layer provides an interface  $broadcast(Message\ msg)$ , which is used by the pub/sub layer to send  $SUB$  messages. Hence, the virtual ring layer is bypassed. The spanning tree layer acts as a filter for the broadcasts. A subscription message sent by a node in the tree is received by parent and child nodes only. Physically it can be received by other nodes too, but these disregard such messages.

To avoid multiple delivery of  $SUB$  messages, they contain the previous sender  $r$  of the message, initially  $r = \perp$ .  $C_S$  contains the identifiers of the subscribed channels and  $P$  all positions of subscriber  $s$ , i.e.,  $P = Pos(s)$ . Distributing the set of channels a node has subscribed to in one message, instead of sending one message per channel (as in [14]), reduces the number of sent  $SUB$  messages by a factor of approximately  $n_c$ . This reduces the network load and thus, the possibility for message collisions.

If a  $SUB$  message from a subscriber  $s$ , forwarded by a node  $u$ , is received by a node  $v$ , then  $RS(v)$  is updated using  $UpdSn(c, SP)$ : If there exists a position  $p_i \in P$ , which is ccw closer than the currently stored next subscriber  $ns$  values in  $RS(v)$ , then it is replaced by  $p_i$  for a given channel  $c$  (details in Algorithm 3). E.g., if  $Pos(v) = \langle 5, 12, 18 \rangle$ ,  $RS(v) = \langle 14, 14, 20 \rangle$ , and the new

subscriber positions are  $Pos(s) = \langle 3, 7 \rangle$ , then the updated routing structure is  $RS(v) = \langle 7, 14, 20 \rangle$ , because position 7 is closer to position 5 than 14.

Before forwarding a message from a node  $u$  the parameter  $r$  is altered by the forwarding node  $v$ , i.e.,  $r := u$ . If a node  $w$  receives a message with  $r = w$ , then  $w$  discards the message. This ensures that a node does not resend a previously send SUB message. Leaves of the tree and subscribers do not forward messages, they only update their routing structure  $RS(v)$ . Algorithm 1 describes the handling of subscription messages.

Figure 3 shows an example, which is kept simple to increase the lucidity. It shows the subscription distribution for a single channel in a line topology. The according virtual ring which does not have any shortcuts is depicted as well. When node  $a$  subscribes for the first time, node  $c$  already is a subscriber. Node  $a$  broadcasts the initial  $SUB\langle \perp, \langle c \rangle, \langle 3, 9 \rangle \rangle$  message. Node  $c$  does not forward it because it is a subscriber itself. Node  $d$  and  $b$  forward the subscription and change the variable  $r$  accordingly. As a leaf, node  $f$  updates its routing structure but does not forward the message. The changes of  $RS$  induced by the subscription of node  $a$  are depicted in 3 (middle).

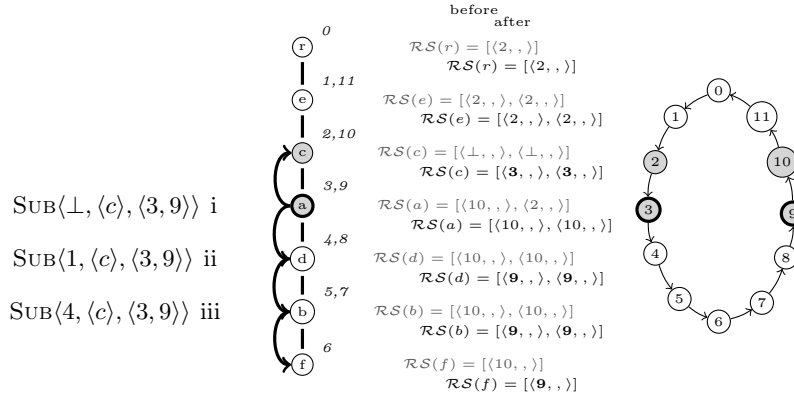


Fig. 3: Node  $a$  with positions 3 and 9 subscribes for the first time to channel  $c$ .

## 4.2 Publications

Publication messages need to be routed to subscribers only. Hence, shortcuts can be used to skip non-subscribing nodes on the virtual ring. Furthermore, publications of nodes with multiple positions can be distributed concurrently over different paths. The following propositions are tied to the fact that the virtual ring is built upon a tree. Under a different scheme the routing still works, but some properties, e.g., that each subscriber receives a publication only once, are not guaranteed anymore.

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**Algorithm 1** Subscribing – pub/sub Layer

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Constants:	$\delta_S$	resubscribe period (leasing period)
Variables:	$C_S$	set of subscribed channels
	$reqRenewalC$	set of channels to be broadcasted
Functions:	$UpdSn(c, SP)$	updates table $RS(v)$ with positions P
Spanning tree layer API:	$broadcast(Msg)$	broadcasts message Msg
	$numChildren()$	returns number children in the tree
<hr/>		
<b>function</b> $subscribe(c)$	Upon $v$ 's reception of $SUB\langle r, C, P \rangle$ from $u$	
<b>if</b> ( $c \notin C_S$ )	<b>if</b> ( $r = v$ )	
$C_S.add(c)$	<b>return</b>	
TIMER_SUB.set(0)	<b>for all</b> $c \in C_S$ <b>do</b>	
	$UpdSn(c, SP)$ ;	
Expiration of timer TIMER_SUB:	$C := C \setminus C_S$ ;	
TIMER_SUB.set( $\delta_S$ )	<b>if</b> ( $C \neq \emptyset \wedge numChildren() > 0$ )	
$broadcast(SUB\langle \perp, C_S, P \rangle)$	$broadcast(SUB\langle u, C, P \rangle)$	

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**Concurrent Routing.** To explain publication routing on the virtual ring and the faced challenges when routing messages concurrently we recap tree-based routing. Each node maintains a routing table to identify branches where at least one subscriber is present. A publisher distributes messages into all such branches concurrently. The same reasoning is conducted by forwarding nodes, while avoiding to send messages back to previous senders. Trees are cycle free, hence, a publication is delivered once per subscriber. In the virtual ring, shortcuts introduce cycles. To avoid message duplication the concept of *routing into a branch* is transferred to the virtual ring. Therefore, the *end of a branch* is defined.

Nodes have multiple positions on the virtual ring, one for each neighbor in the tree. Hence, sending a message from every position in  $Pos(v) = \langle p_1, \dots, p_s \rangle$  to  $p_1 + 1, \dots, p_s + 1$ , respectively is the equivalent of a tree node sending into all branches. In the routing structure  $RS$  the next subscriber for each position is stored, this reflects a node's understanding that a subscriber exists in a certain tree branch. Therefore, if a publisher knows that there is at least one subscriber in an interval  $\mathcal{I} = [p_i, p_{i+1})$  for a given channel  $c$  then it sends a publication to a *goal* position in  $\mathcal{I}$ . The *goal* position is the ccw closest one-hop reachable position to the next subscriber in  $\mathcal{I}$ , i.e., *goal* is either the next position on the virtual ring or a position reachable by a shortcut.

Received publications are delivered to all nodes subscribing to the message's channel. Regardless of the delivery, publications are forwarded to ensure that all subscribers receive it. Forwarding of publications is restricted to the interval they are sent into. To avoid sending messages beyond interval borders the endpoint  $ep$  of each  $\mathcal{I}$  is attached to publication messages:  $PUB\langle goal, ep, c, data \rangle$ . Where  $ep$  is the right endpoint of  $\mathcal{I} = [p_i, p_{i+1})$ , i.e.,  $ep = p_{i+1}$ . A message is neither routed to  $ep$  nor to a position beyond it. Parameters *goal* and *ep* are updated at every forwarding node. Parameter *data* represents the payload.

The start position of an interval is the current position of a node and the endpoint position is defined by the ccw next position of the same node. Multiple



delivery of a publication to nodes with multiple positions in an interval is avoided as shown in Lemma 1.

**Lemma 1.** *The positions of nodes on the virtual ring are never interlaced. That is, a node  $v$  may have a position on the virtual ring which is followed by a node  $w$ 's position, once another position of  $v$  appears there cannot be a further position of  $w$ .*

*Proof.* The virtual ring is derived from a tree. A node has multiple positions if and only if it has children in the tree. All positions of a child branch are therefore nested in between two of its parents positions.

As Lemma 1 suggests, within a nodes's interval  $\mathcal{I}$  may be further intervals of other nodes. For the routing this means, that a node forwarding a publication applies the same reasoning as a publisher to determine how to forward messages. In the tree this corresponds to branching. Each branch containing a subscriber leads to an additional message sent concurrently. The analog in the virtual ring is as follows: Each subscriber in the interval  $\mathcal{I}_f = [p_i, p_{i+1})$  with  $p_{i+1}$  ccw in between  $p_i$  and  $ep$  forwards the PUB message. That is, in the *subsection* of the virtual ring bounded by the current node position and the received endpoint position  $ep$ , independent concurrent routing is conducted. Therefore, the parameters of the PUB message are updated. The endpoint becomes  $p_{i+1}$  if  $p_{i+1}$  is ccw between  $p_i$  and  $ep$  otherwise it stays unchanged.

Algorithm 2 shows the handling of publications and the calculation of associated endpoints. When a node generates a publication with content *data*, then the *handlePub()* function is called, i.e., message  $\text{PUB}\langle P[0], P[0], c, data \rangle$  is sent.

**Theorem 1.** *In error-free phases subscribers receive PUB messages exactly once.*

*Proof.* Once a position receives a publication message it is distributed over all possible positions with updated  $ep$ . This is equivalent to routing messages into branches of the underlying tree. Since parameter  $ep$  of a publication is closer or equal to the next position of the same node when the message is forwarded, it is assured that no further position of the same node receives a message again. For a particular position of a node, routing is conducted using a tree edge or a shortcut. A shortcut can only be used if  $RS(v)$  ensures that no subscriber is skipped. Hence, in the range of the tree between the position the shortcut leads to and the tree position which would be used instead (incremented current position) no subscriber exists.

To illustrate the advantage of using shortcuts consider the topology and the virtual tree graph in Fig. 5a and 5b. In pure tree routing a message from node  $c$  to  $d$  is sent via node  $e$ . With  $\mathcal{PSVR}$  the direct shortcut between node  $c$  and  $d$  is taken. The table in Fig. 5c shows the *next subscriber* and the *goal* positions. The next subscriber is the according entry in  $RS$  for the stated position. The publisher initiates two delivery paths, one for each position, i.e., for each interval. In the virtual ring in Fig. 5b these subsections are depicted as light gray areas. One

subsection starts at position 6 the other at 8 while  $ep$  is the start position of the next subsection, respectively. Publisher  $d$  sends messages  $\text{PUB}\langle 7, 8, c, data \rangle$  from position 6 and  $\text{PUB}\langle 2, 6, c, data \rangle$  from position 8. Position 2 forwards the publication in one interval with the borders  $[2, 4)$  with the message  $\text{PUB}\langle 3, 4, c, data \rangle$ . In Fig. 5b this is represented by the dark gray area. In the interval  $[4, 6)$  no subscriber exists, hence, no message is sent into the respective subsection.

Figure 4 shows an execution of Algorithm 2. A virtual ring with shortcuts is depicted. Furthermore, the table next to the ring shows the routing table  $RS(v)$  for each node and a single channel, with each of its own positions ( $Pos$ ). A table cell represents one node, e.g., the first node has the positions 0, 8, 12, and 14. Publishers are depicted as black circles, and subscribers as gray ones.

**Detailed Example for Parallel Publication Routing** In Fig. 4 two publishers exist, one at positions 1, 3, and 7 (referred to as node  $a$ ) and at position 15 and 19 (node  $b$ ). Both publishers send one message for each interval  $[p_i, p_{i+1})$  a subscriber is present (see schedule for (a) and (b)).

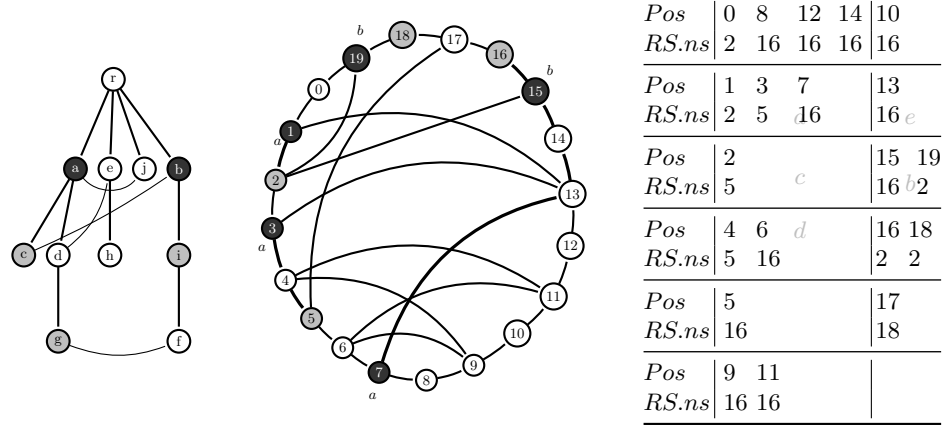


Fig. 4: Publication routing example on virtual ring. Black and gray positions are publishers and subscribers, respectively.

	from		to	$ep$		from		to	$ep$
(a)	1	->	2	3	(b)	15	->	16	19
	3	->	4	7		19	->	2	15
	7	->	13	1					

When a subscriber receives a publication, it delivers the message, then it evaluates if the message has to be forwarded. If one or more subscribers exist

within the received  $ep$ , and if the calculated goal position does not lie beyond any of its other positions or the received  $ep$ , then a new  $ep$  is calculated and the message is altered before it is sent.

We focus on the publication from node  $a$ . Positions 2, 4, and 13 received the publication and forward the message according to the schedule for  $\textcircled{c}$   $\textcircled{d}$   $\textcircled{e}$ .

	from	to	$ep$		from	to	$ep$		from	to	$ep$	
$\textcircled{c}$	2	not		$\textcircled{d}$	4	->	5	6	$\textcircled{e}$	13	-> 14	1
					6	not						

Position 2 does not forward the message since the  $ep$  is 3. Position 4 sends a message to 5 which is not forwarded by 5 because the  $ep$  was changed from 7 to 6 which is another position from the node at position 4. Finally, the message from position 13 is forwarded.

At position 14 only one message is sent, the one with destination position 15, because the  $ep$  is still 1 and positions 8, 12, and 14 (all belong to the same node) have the same next subscriber position. Nevertheless, the  $ep$  is changed at position 14 to 0. Position 15 forwards to 16.

At 16 the message is delivered. Position 18, which is the second position of the node at position 16, does not forward the publication, because the next subscriber, position 2, is beyond the current  $ep$  (0). Therefore, the publication is not forwarded any further, which is desired since all subscribers got the publication.

In this example seven messages are sent to deliver the publication. With the algorithm in [14] twelve messages are necessary. With  $\mathcal{PSVR}$  positions 8 to 12, and position 17 are skipped.

**Resolving drawbacks of [14].** In the related work section two shortcomings of [14] concerning publications were mentioned. Firstly, *nodes receive publications multiple times*. For the example in Fig. 5 this means that the path a PUB message travels, starting at position 6 is:  $\langle(6), 7, 8, 2, 3, 4\rangle$ , i.e.,  $\langle(d), b, d, c, a, c\rangle$ . Node d (positions 6 and 8) receives its previously published message in order to forward it. Additionally, node c receives the same publication twice. As can be examined in Fig. 5b, with  $\mathcal{PSVR}$  two messages travel:  $\langle(6), 7\rangle\langle(8), 2, 3\rangle$ , i.e.,  $\langle(d), b\rangle\langle(d), c, a\rangle$ . This is a considerable improvement.

Secondly, *publications travel further on the virtual ring as the last subscriber*. Consider an example where the next subscriber  $p_w$  lies beyond a publisher  $p_v$ , as depicted in Fig. 6. In [14] a publication from  $p_v$  is forwarded until a node at position  $p_u$  can determine that forwarding leads to routing the message past or to the original publisher  $p_v$ , then the node ceases forwarding. With  $\mathcal{PSVR}$ , due to the definition of the end position  $ep$  and the knowledge of the next subscriber  $p_w$ , such a situation is recognized by the ccw *last* subscriber  $p_t$  before publisher  $p_v$ .  $p_t$  checks if the next subscriber is between the current position and  $ep$ . If this is not the case, the message is not forwarded. Hence, in Fig. 6 four avoidable messages, starting at position 3 successively to position 7, are sent with [14] compared to  $\mathcal{PSVR}$ .

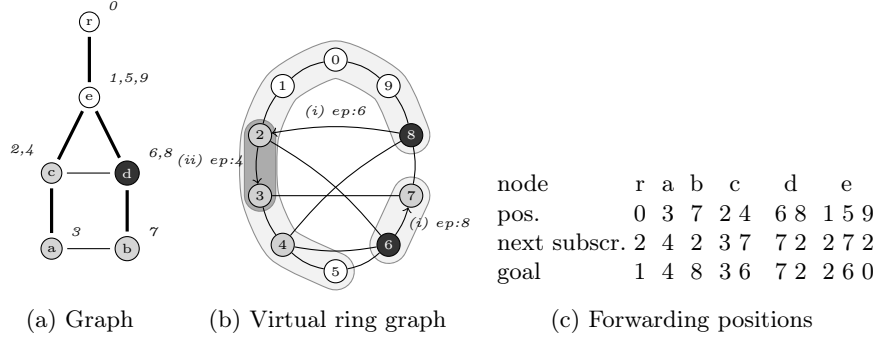


Fig. 5: Illustration of the forwarding process (Subscribers: gray; publisher: black)

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**Algorithm 2** Handling and forwarding of publications

---

**API provided by virtual ring layer (VR):**

*getPosClosestTo*( $p$ ,  $goal$ ) returns largest ccw position beyond  $p$  and prior (or equal to)  $goal$  within neighbor positions  
*sendOnRing*( $p$ ,  $msg$ ) sends message  $msg$  to position  $p$   
*isBetween*( $test$ ,  $left$ ,  $right$ ) checks if position  $test$  is in ccw ring segment bounded by positions  $left$  and  $right$   
 note:  $isBetween(x, y, y) = true$  for arbitrary positions  $x$  and  $y$   
*deliver*( $data$ ) delivers the  $data$  to the application

---

**function** *publish*( $c$ ,  $data$ )  
**handlePub**( $P[0]$ ,  $P[0]$ ,  $c$ ,  $data$ )

Upon reception of  $PUB\langle curPos, ep, c, data \rangle$   
**if** ( $c \in C_S$ )

**deliver**( $data$ )  
**handlePub**( $curPos, ep, c, data$ )

**function** *handlePub*( $curPos, ep, c, data$ )  
**for all**  $p \in P$  **do**  
 $nextS := RS[indexOf(c)][indexOf(p)]$   
 $newEp := calcNewEP(p, ep)$

---

**if** ( $isBetween(nextS, curPos, newEp)$ )  
 $goal := getPosClosestTo(p, nextS)$   
**sendOnRing**( $goal$ ,  
 $PUB\langle goal, newEp, c, data \rangle$ )

**function** *calcNewEP*( $p$ ,  $maxEp$ )  
 $i := indexOf(p)$   
 $epIndex := i + 1 \bmod |P|$   
**if** ( $isBetween(P[epIndex], p, maxEp)$ )  
**return**  $P[epIndex]$   
**else**  
**return**  $maxEp$

---

### 4.3 Implicit Unsubscription Handling

A node  $v$  that ends a subscription to a channel removes the respective channel identifier from  $C_S$ . If  $C_S$  becomes empty, then  $v$  ceases to send SUB messages. This triggers updates in the routing structure  $RS$  at other nodes. If a value in  $RS$  has not been renewed after the leasing period  $\delta_S$ , then it is identified as *stale*. Stale entries are used for routing nonetheless, i.e., for incoming publication forwarding the staleness of the entry is irrelevant. When a SUB message with a ccw closer subscriber position is received, the stale value is replaced and timestamp  $t_s$  is renewed.

If a stale value is not replaced in this way, then a temporary new next subscriber  $nstmp$  is stored when the next SUB message is received. This  $nstmp$  value

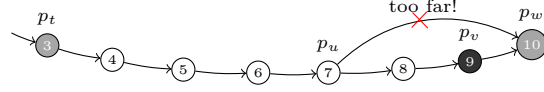


Fig. 6: Virtual ring section. Shortcoming of [14]: unnecessary forwarding

is treated the same way as the according stale value in  $RS$ . Initially  $nstmp := \perp$ . When a SUB message is received  $nstmp$  is set to the closest ccw subscribing position stated in the message. For every received SUB message  $nstmp$  is updated to store the closest ccw subscriber position. While  $nstmp$  is updated, routing for PUB messages still refers to the stale value. After an update period  $T_{w/back}$   $nstmp$  replaces the stale value  $ns$ . The time-stamp  $t_s$  is set to the current time and  $nstmp$  resets to  $\perp$ . Algorithm 3 describes the details of the already mentioned  $UpdSn()$  function.

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**Algorithm 3** Unsubscriptions

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Constants: $T_{clean}$	clean timer expiration time
$T_{w/back}$	write back period $\rightarrow$ temp value replaces stale value
Functions: $isStale(t_s, exptimer)$	return $currentLocalTime() - t_s > exptimer$

---

```

function  $UpdSn(c, SP)$                                      //TIMER_CLEAN initialized on system startup
  for all  $sp \in SP$  do                                       Expiration of timer TIMER_CLEAN:
    for all  $rs_j \in RS[c]$  do                                  TIMER_CLEAN.set( $T_{clean}$ )
      if ( $isBetween(sp, P[j], rs_j.ns)$ )                     for all  $rs \in RS$  do
         $rs_j.ns := sp$                                        if ( $isStale(rs.t_s, T_{w/back})$ )
         $rs_j.t_s := currentLocalTime()$                       $rs.ns := rs.nstmp$ 
      else if ( $isStale(rs_j.t_s, \delta_S)$ )                    $rs.t_s := currentLocalTime()$ 
        if ( $isBetween(sp, P[j], rs_j.nstmp)$ )              $rs.nstmp := \perp$ 
           $rs_j.nstmp := sp$ 

```

---

Routing is correct during the whole process, that is, no subscriber is skipped. When a node unsubscribes or an error in  $RS$  occurs, it takes at most  $T_{w/back}$  periods of time until  $RS$  is consistent again. The burden on memory for the presented unsubscribing scheme is manageable. For each node position the temp value and  $t_s$  has to be accounted for, typically for each node that means  $(2+4)C_N$  Bytes. Note that  $\delta_S$  can be constant or determined during runtime, as it has a strong correlation to the length of the virtual ring. When the virtual ring is constructed the root node sends a DOWN message including starting positions of each node into the ring [14]. The root node has knowledge of the tree and the ring size. Hence, attaching this value to the DOWN message of the virtual ring setup algorithm can be realized conveniently. The number of nodes, i.e., the length of the ring can then be used to calculate  $\delta_S$ .

#### 4.4 Self-stabilizing Properties

Self-stabilization is ensured by the leasing technique. Through the periodic renewal of subscriptions routing tables are continually updated and errors are fixed. Storing a time-stamp of the last update  $t_s$  in the routing structure  $RS(v)$  ensures that stale values can be recognized. Hence, inconsistencies due to message errors, loss, or obstruction are corrected. Proper publication routing is ensured by the correctness of  $RS(v)$ . Unsubscribing is self-stabilizing as well. To unsubscribe from a channel a node removes the channel identifier from  $C_S$ , this ceases sending SUB messages. The underlying structures, virtual ring and spanning tree are built using self-stabilizing algorithms. They are tied together using collateral composition where a layer does not influence a layer below.

Self-stabilizing algorithms inherently can not locally decide if the system is in a globally correct state. Thus, in a faulty case no guarantees can be given, but that eventually the system will recover.  $\mathcal{PSVR}$  handles dynamic addition and removal of nodes, after addition to the virtual ring and the dispatch of the first SUB message it takes no longer than  $O(n)$  rounds until PUB messages will be received.

### 5 Evaluation

$\mathcal{PSVR}$  presents a compromise of size and maintenance effort for routing tables and routing paths lengths. In order to assess the increase of the path's lengths a comparison with two routing strategies was done. In alternative  $\mathcal{T}_D$  we computed a breadth-first tree for each node and recursively pruned leaves not corresponding to subscribers. Publications made by a node were forwarded via the corresponding bfs-tree. Alternative  $\mathcal{T}_S$  followed the common approach of a single routing tree. We chose a bfs-tree rooted at a central node. The first alternative comes close to the optimal structure, i.e., a Steiner tree. We analyzed connected graphs  $G(n, p)$  using the Erdős-Rényi model. The message gain in percent is calculated by  $100B/A - 100$ , where  $B$  is the number of messages needed by  $\mathcal{PSVR}$  and  $A$  is the number of message needed by the approach it is compared to.

The results indicate that the difference between average path lengths decreases with increasing density and with an increase of the number  $s$  of subscribers. In Fig. 7 the gain for both approaches compared to  $\mathcal{PSVR}$  is depicted. For example for  $n \leq 100$  and  $s \geq 10$  the overhead of  $\mathcal{PSVR}$  is less than 8 %. The same trend – but at a lower level – was observed for  $\mathcal{T}_S$ . We conclude that except for very small numbers of subscribers the overhead of  $\mathcal{PSVR}$  with respect to path lengths is surprisingly low. With increasing density the number of shortcuts increases, allowing for shorter routing paths. Furthermore, with growing number of nodes the gain follows the same distribution.

Next we analyzed the delivery ratio using implementations based on the OMNeT++ simulation environment and the MiXiM framework to employ a radio model compared to the self-stabilizing tree based approach by Shen et al. [13]. Both approaches, Shen and  $\mathcal{PSVR}$  use the same dynamically computed spanning tree. The throughput of both approaches is close to identical as presented in

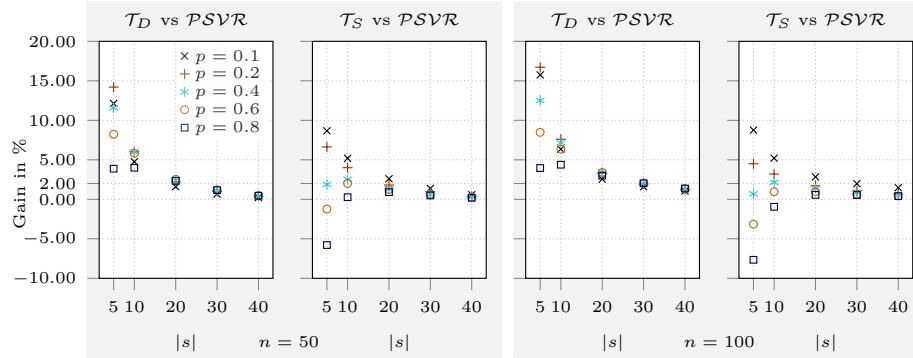


Fig. 7: Comparison of  $\mathcal{T}_D$  and  $\mathcal{T}_S$  vs  $\mathcal{PSVR}$

Fig. 8. Even though  $\mathcal{PSVR}$  needs to maintain the virtual ring structure, shorter routes as depicted in Fig. 9, compensate this handicap.

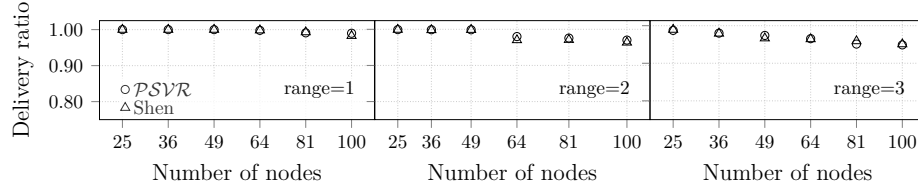


Fig. 8: Publication delivery for varying densities, compared to Shen's approach.

Figure 9 shows the constructed path lengths for simulations involving a radio model and the complete network stack described in Section 3. The depicted histogram shows the route lengths for a scenario with a single subscriber and each node is a publisher. As can be seen  $\mathcal{PSVR}$  constructs more short routes (i.e., up to 3 hops) as well as shorter routes on average than Shen's algorithm. Increasing the number of subscribers diminishes the gain of  $\mathcal{PSVR}$  to the point that all nodes are subscribers and no shortcut is taken anymore but  $\mathcal{PSVR}$  resembles routing on a spanning tree, i.e.,  $\mathcal{PSVR}$  falls back to the Shen's approach.

The gain varies substantially depending on the density (density grows with communication *range*) as can be seen in the boxplots in Fig.10. The denser the network the more potential shortcuts, hence, the gain in saved messages is increased. This also holds for the simulations with OMNeT++ and the applied radio model (includes path loss and slow fading).

### 5.1 Real World Deployment: Throughput and Robustness

$\mathcal{PSVR}$  delivers all publications while no error in the underlying routing structure occurs. Figure 11 shows the delivery ratio in percent for multiple tests on a real sensor network deployment at the Fit-IoT Lab in France [5]. For each number of

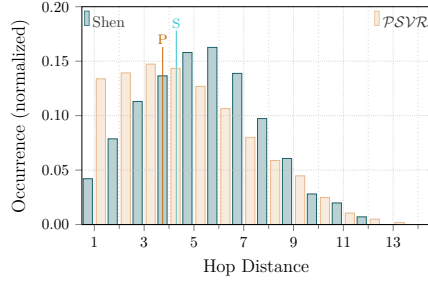


Fig. 9: Hop distances of delivery paths. Average distance depicted by  $S$  for Shen's approach and  $P$  for  $\mathcal{PSVR}$ .

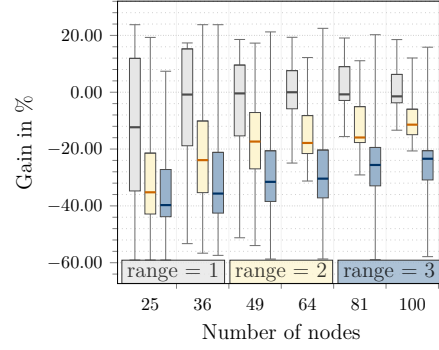


Fig. 10: Average gain per subscription.

nodes 20 tests are conducted each lasting two hours. An initial setup phase of 10 minutes is granted until publication delivery starts. Publications were dispatched every 20s. In Fig. 11 (right) the same experiment is run for ten hours. Whenever an error occurs in the network the publication delivery ratio decreases, in error free phases the value can recover. The figure shows a single representative example for 10, 20, and 50 nodes. As the Fit-IoT Lab can be used at the same time by other people, possibly executing bandwidth demanding experiments, a long term test shows the recovery strength of our approach.

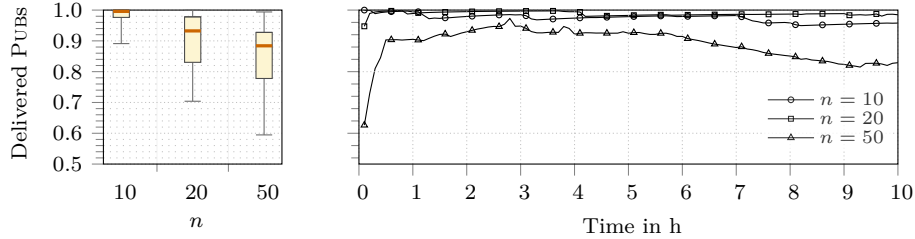


Fig. 11: Delivered publications average and long term test snap shot.

As can be seen by Fig. 11 (left) unsurprisingly an increasing number of nodes is more demanding on the pub/sub system. In short periods of time and mostly when the wireless channel is in use by other experiments the delivery ratio decreases. As can be seen in Fig. 11 (right), the 10 minute setup period was occasionally too short for the 50 nodes experiments also causing a drop in the delivery turnout. On average it stayed in the 80% to 90% margin, which we find tolerable considering the benefits of inherent fault tolerance and dynamic adaptability.



## Conclusion

The presented pub/sub system *PSVR* significantly enhances the algorithm of [14]. *PSVR* is optimized for scenarios where communications links are unstable and nodes frequently change subscriptions. It is a compromise of size and maintenance effort for routing tables due to sub- and unsubscriptions and the length of routing paths. Simulations and verification against theoretical, closer to optimal solutions revealed that our approach gives a fair trade-off between the scalability of the support structure and the message forwarding overhead. Real world tests confirmed its usability. The approach scales with the number of nodes and is suitable for wireless ad-hoc networks.

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